REPORT No. 18

AEROFOILS AND AEROFOIL STRUCTURAL COMBINATIONS

By LIEUT. COL. EDGAR S. GORRELL, S. C.

AND

MAJ. H. S. MARTIN, S. C.

Thesis prepared at Massachusetts Institute of Technology under direction of Alexander Klemin and T. H. Huff.

REPORT NO. 18.

AEROFOILS AND AEROFOIL STRUCTURAL COMBINATIONS.

By EDGAR S. GORRELL and H. S. MARTIN.

INTRODUCTION.

FORMULÆ NOTATION.

(Pounds, square feet, miles per hour units.)

A.=Area of aerofoil in square feet. The brass model aerofoils were 18 by 3 inches.
C. P.=Center of pressure; i. e., the point of intersection of the resultant vector of forces with the plane of the aerofoil's chord.
D=Drag of the aerofoil as given by $D-K_xAV^2=D_1-D_0-D_s$.
Density=Density of standard air; i. e., 0.07608 lbs./cu. ft.
D_0=Drag of the aerofoil when $V-O$.
D_1=Drag of the aerofoil at the correct V for the test.
D_s=Drag of the spindle used as a spindle correction.
i=Angle of incidence; i. e., angle of wing chord to the wind.
K_x=Drag coefficient used in the standard formula $D=K_xAV^2$.
K_y=Drag coefficient used in the standard formula $L=K_yAV^2$.
L=Lift of the aerofoil as given by $L=K_yAV^2=L_1-L_0$.
L/D=Ratio of lift to drag.
L_0=Lift of the aerofoil when $V=O$.
L_1=Lift of the aerofoil at the correct V for the test
M=Moment of resultant vector$=\frac{M_1-M_0}{3.65}$ for M. I. T. balance.
M_0=Moment of resultant vector when $V=O$.
M_1=Moment of resultant vector at the correct V for the test.
V=Velocity of the wind; i. e., 30 miles per hour for these tests.

Mathematical theory has not, as yet, been applied to the discontinuous motion past a cambered surface, using the term cambered as generally understood in aeronautics. For this reason, we are able to design aerofoils only by consideration of those forms which have been successful, by applying general rules learned by experience, and by then testing the aerofoils in a reliable wind tunnel. A great many aerofoils have from time to time been tested and from them we know general rules which must be observed concerning camber and the variations of camber on the upper and lower surfaces, if we are to expect to attain even fair results. Results better than the ordinary are only attained when these general rules are observed, and patience and good fortune are combined. There are equations of curves which are very much like some aerofoils but they are not deduced from mathematical knowledge of the flow past an aerofoil but rather from the knowledge of the shape of these curves, and a good idea of the shape of a satisfactory aerofoil. It seems possible that eventually we shall know mathematically the best form for speed and climb, but the practical application of this knowledge may be more difficult than the present method of designing.

OBJECT OF THE TEST.

Although a great many aerofoils have been tested, many are useless from a practical point of view. It seems safe to assert that in this country nearly every aerofoil used is either one of the best five or six tested by M. Eiffel near Paris or by the National Physical Laboratory at Teddington, England, or based upon them, with some slight modifications. As will be seen from the results of these tests apparently slight variations may make considerable differences.

We are thus limited to a few aerofoils, and some of these lack certain desirable characteristics as to the depth of wing spars combined with aerodynamical efficiency. It would seem of advantage to have the following results of the tests made upon the six structurally excellent and heretofore aerodynamically unknown aerofoils designed by the Aviation Section, Signal Corps, United States Army. This constitutes the largest single group of aerofoils, excepting those of the N. P. L. and M. Eiffel, which has been tested and published.

DESIGN OF THE AEROFOILS.

U. S. A. 1 is a modification of the Clark aerofoil to receive a deeper rear spar. It was designed to be a good high-speed wing, with a good $\frac{L}{D}$, having at the same time sufficient rear spar depth.

Depth of front spar = 0.0584 chord.
Depth of rear spar = 0.0497 chord.

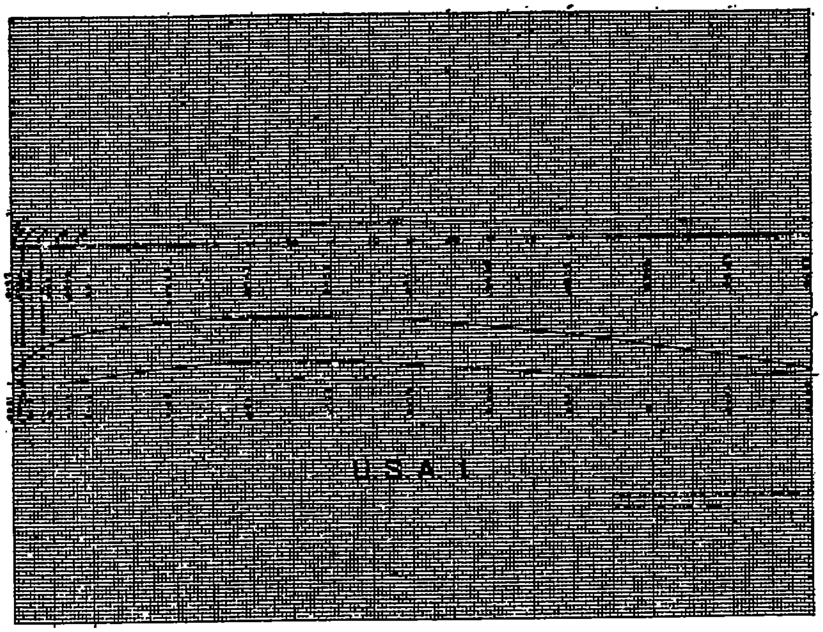
U. S. A. 2 is a combination of the good characteristics of both R. A. F. 3 and R. A. F. 6. It is an aerofoil designed for use in a biplane combination as follows: The depth of the front spar measured along a line making an angle of 10° 45′ (angle of stagger) with the vertical is 0.875 that of R. A. F. 6. The depth of the rear spar is 0.88 that of the front spar of U. S. A. 2. The center of the front spar is 0.12 of the chord, and the center of the rear spar is 0.70 of the chord, from the leading edge. The curve of the upper surface is R. A. F. 3 and that of the lower surface is R. A. F. 3 lowered and modified to take the deeper spars.

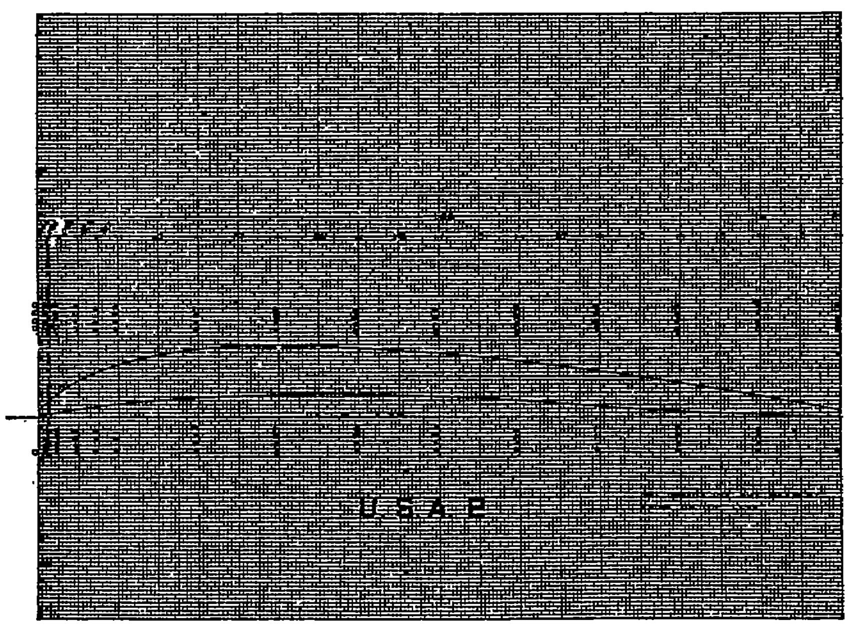
U. S. A. 3 has the same structural features of U. S. A. 2. The nose is moved *forward* $\frac{3}{8}$ inch and the ordinates are measured and calculated as a ratio of a $30\frac{3}{8}$-inch chord. These ordinates are then transposed to a 30-inch chord. The rear 0.8 of U. S. A. 3 is identical with the rear 0.8 of U. S. A. 2 and the changes necessitated occur in the leading 0.2 of the aerofoil.

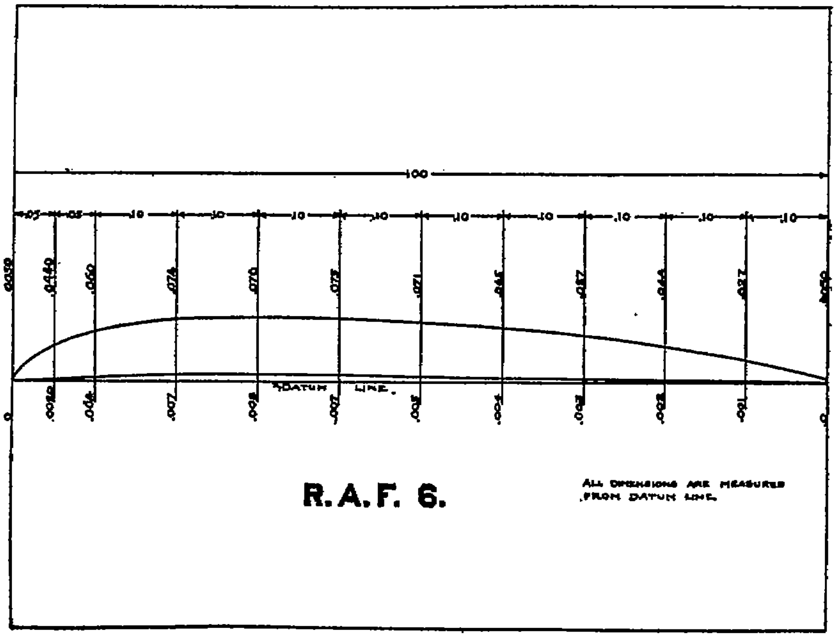
U. S. A. 4 was designed as indicated for U. S. A. 3 except that the nose was moved $\frac{3}{8}$ inch *backward* instead of forward as in U. S. A. 3.

U. S. A. 5 is not based upon any particular wing section but upon a general consideration of the factors necessary to result in an aerodynamically and structually efficient areofoil.

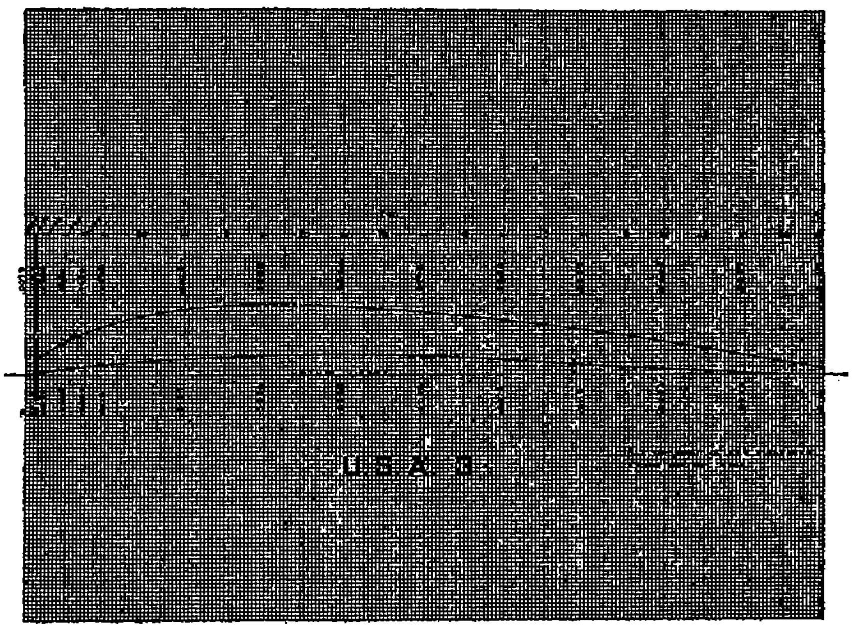
U. S. A. 6 is designed from the basic principles of a certain foreign aerofoil that has rendered particularly good results in the European conflict.


U.S.A. 1

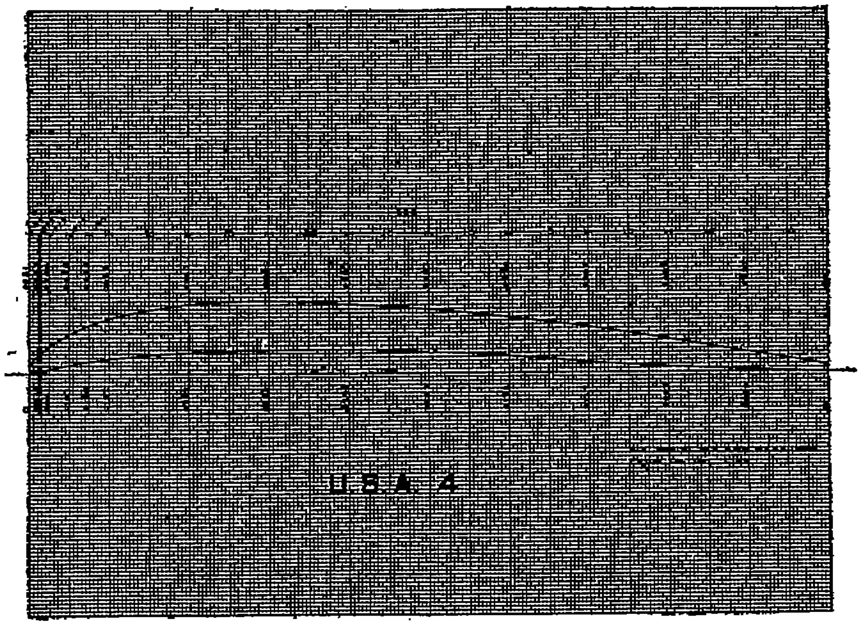

U.S.A. 2

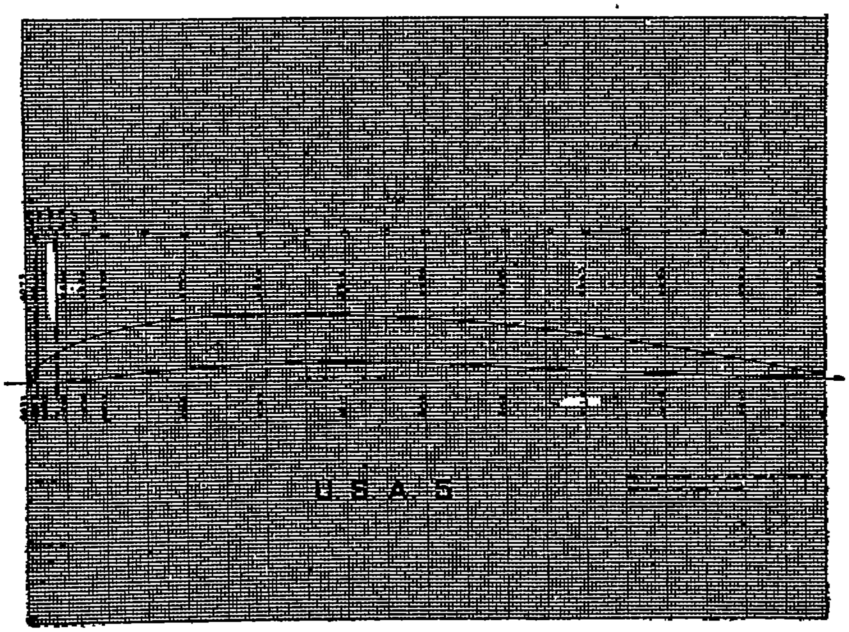


R. A. F. 6.



U. S. A. 3


U.S.A. 4

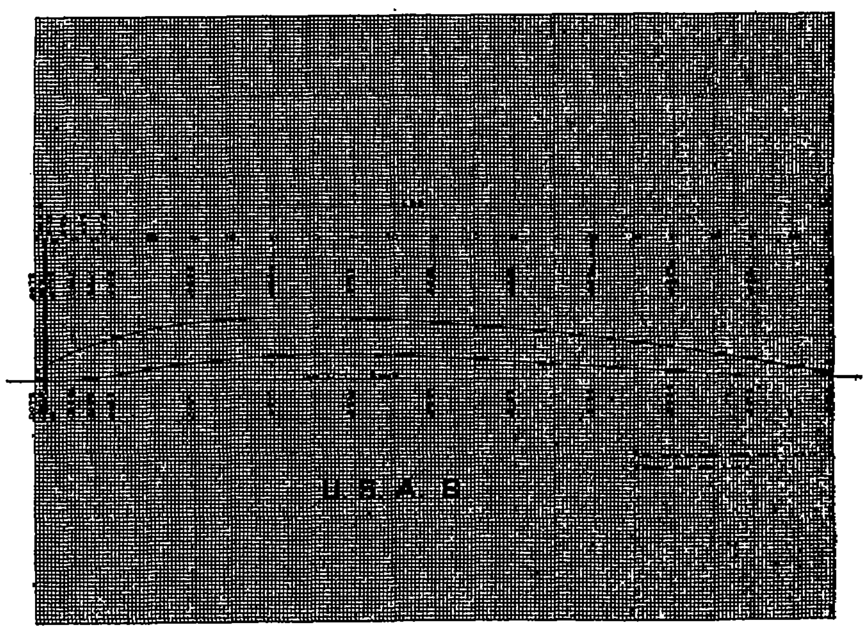

U.S.A. 5

CONSTRUCTION OF THE U. S. A. AEROFOILS.

The brass aerofoils were constructed by the Industrial Manufacturing Co. of Camden, N. J., which firm is well known for the accuracy of its work. The method used is briefly indicated as follows:

The drawings to a scale based on a 30-inch chord were furnished to the company. The company turned the drawings over to its tool designer with instructions to him to get out the necessary tools for the work. These instructions resulted in his having made a heavy milling arbor to take a two-piece fly cutter, the reason for this two-piece fly cutter being because of the width of the cut and the thinness of the models.

The tool designer next secured a plate about ½ inch thick by 5 by 24 inches, which was machined all over with tongs inserted on one side,



for the purpose of locating it centrally on the milling machine. Four low stops were inserted at the end of this plate to take the thrust of the cut.

The patterns and castings were made in the usual way. The scale was taken from the castings, and they were then relieved of all strains by a heat treatment.

They were then turned in strips 1 inch wide across the width of the model and the plate treated in the same manner, and they were then ready to be sweated together. After this they were ready for the milling operation of the first side, which, of course, was the concave or underside of the aerofoil.

It was decided that the use of single-edge fly cutters would be the quickest and most accurate method for the milling operations, so that method was adopted.

In order to plot the curves to model size, a master layout was necessary. To this end, a face plate, fitting a universal dividing head was made and the layout was secured in the following manner: A piece of zinc was utilized for the template, which was thoroughly cleaned and polished. It was coated with a mixture of a saturated solution of copper sulphate and hydrochloric acid. The zinc then presented a fine jet-black surface, which was then fastened to the face plate on the universal dividing head, the same being mounted on a perfectly finished surface plate. The datum lines and all the lines of intersections were then drawn with a height gauge. The single-edge fly cutters were made to harmonize with the curves of the master layout and the aerofoils were then milled to within 0.01 of the finished size from the datum line. Sweating pads were left on the machined side of the aerofoil, and were full length of the casting. These were tinned and sweated onto plate, as in the first operation.

The underside of the aerofoil was filled with plaster of Paris and allowed to harden, after which the second side was machined to within the same limits as the first.

The finishing was, of course, done on the bench, the surface plate and height gauge being used to determine the points of measurement, and the measurements taken with micrometers with special points made for this purpose. In this way they were finished to the ultimate measurements by hand, which was a tedious, but very interesting operation, owing to the precision required.

All upper surfaces are correct to 0.001 and all lower surfaces are correct to 0.002.

METHOD OF CONDUCTING TESTS.

The model aerofoils were held in the ordinary position in the wind tunnel by a vertical spindle attached to the balance. The angle of incidence was varied and observations were made to determine the components of force directed down the stream and across the stream, as well as the twisting moment about a vertical axis passing through the supporting spindle. Forces are measured directly in pounds and moments in inch-pounds on the model for a wind velocity of 30 miles per hour. The density of the air is 0.07608 pounds per cubic foot.

The results obtained in pounds for the forces were substituted in the standard formulæ $L=K_y A V^2$ and $D=K_x A V^2$, thereby giving the desired values of the lift and drift coefficients.

The moments about the vertical axis through the spindle M were measured on a torsion wire. Likewise, the longitudinal and lateral components of the resultant wind force were observed, i. e. R_x and R_y. The total resultant force is then $R=\sqrt{R^2_x+R_y^2}$. The direction of this force is at the angle $=\tan=\frac{1\ R_y}{R_x,}$ measured from the axis of the tunnel. The resultant force has an arm. Thus, $A=\frac{M}{R}$. The force R is then determined in magnitude, direction, and point of intersection with the plane of the aerofoil's chord. Thus is determined the center of pressure curve.

DISCUSSION OF THE RESULTS.

The results in no way contradict any of the known general principles regarding the effects of changing variations in the camber of aerofoils. There are rules for determining the relative value of different wing sections. The lift-drift ratio, which is a measure of the efficiency of an aerofoil, gives information as to the value of the wing. The qualities desired in a good aerofoil are high speed, or low resistance, great climbing ability, and excellent weight carrying capacity. Any one of these characteristics may be secured, but only at the expense of the other two to a certain extent. In a pursuit machine, where compromises are made to secure both high speed and excellent climbing ability, weight carrying is sacrificed. In a bombing machine weight carrying ability is desired to the partial sacrifice of speed and climb. In a training machine all three characteristics are desired, but in moderation. A machine designed for high speed alone has only a limited practical application.

It is generally conceded that there is no "best" aerofoil, for all have different characteristics and perform different functions. The selection of a desirable section depends on the performance required of the airplane desired.

All of the U. S. A. aerofoils have the fundamental quality of being structurally sound, permitting the use of sufficiently deep wing spars.

As suggested in Mr. Alexander Klemin's "Course in Aeronautics," the U. S. A. aerofoils are considered under the following headings:

(*a*) The maximum value of $\frac{L}{D}$, the angle at which it occurs, and the corresponding K_y.—The reason for this comparison is that an airplane in normal horizontal flight will generally be navigated at the angle giving the best $\frac{L}{D}$ ratio, which is therefore important from an efficiency point of view. The value of the lift coefficient at the best $\frac{L}{D}$ ratio is important because the greater the lift at this ratio the smaller the area of the wing surface required for the load. With a heavy machine a big lift coefficient is desirable. With a pursuit or racing machine a good $\frac{L}{D}$ at small angles is desirable, so that with a sufficiently powerful motor a great speed may be obtained.

(*b*) The maximum K_y, the angle at which it occurs, and the corresponding $\frac{L}{D}$ ratio.—The maximum K_y is a very important characteristic. The greater the maximum K_y the slower is the speed at which a machine may fly and land. If large values of K_y are accompanied by good $\frac{L}{D}$ ratios, then the machine will be efficient in climbing, though the best angle of climb is by no means at that of the maximum K_y. If the maximum K_y occurs at a high angle, then there are possibilities of good speed range.

(*c*) The shape of the burble point.—If the lift past the burble point falls off very rapidly, the airplane can be quickly stalled. On the other hand, a wing with a flat lift curve at the burble point will avoid quick stalling. In all the U. S. A. aerofoils the shape of the curves at the burble points is sufficiently flat to be satisfactory.

(*d*) The $\frac{L}{D}$ ratio at small angles of incidence and small values of K_y determine whether or not the aerofoil is really suitable for high speeds. We conform to Mr. Klemin's comparison value of $K_y=0.00086$.

(*e*) Movement of center of pressure at low angles.—The importance of this fact is readily apparent from consideration of stability. In all the U. S. A. aerofoils the movement of the center of pressure is not prohibitive or unsatisfactory.

(*f*) Structural considerations are satisfactory in such aerofoils.

(*g*) Subheads (*a*), (*b*), and (*d*) are tabulated herewith for convenience of reference.

		Maximum $\frac{L}{D}$.			Maximum K_y.			K_y—0.00086.	
Wing.	LV—chord of wing in feet $\times$ relative wind in feet-seconds.	Angle in degrees.	K_y.	$\frac{L}{D}$	Angle in degrees.	K_y.	$\frac{L}{D}$	Angle in degrees.	$\frac{L}{D}$
U. S. A. 1	11	3.0	0.00133	17.8	15.0	0.00318	9.6	0.62	12.9
U. S. A. 2	11	4.0	.00169	16.3	15.0	.00337	9.3	.0	9.9
U. S. A. 3	11	4.0	.001704	16.4	13.6	.003243	9.8	.3	10.4
U. S. A. 4	11	4.0	.00177	15.88	15.0	.00364	9.1	.35	9.1
U. S. A. 5	11	3.0	.001565	16.21	14.0	.003285	9.25	.18	11.8
U. S. A. 6	11	3.0	.001455	17.4	14.0	.00298	7.37	.1	13.3

U. S. A. 1, its maximum $\frac{L}{D}$ of 17.8, the highest of any U. S. A. aerofoils, occurs at 3.0°, at which point its center of pressure motion is fairly rapid but not so rapid as to make the aerofoil undesirable. This aerofoil would be undesirable as the wings of a very heavy machine, but it is very desirable as the wings of a fast pursuit machine. Its maximum K_y is sufficiently large to warrant a reasonable landing speed. Its $\frac{L}{D}$ at small values of K_y is excellent and usually better than any of the other U. S. A. aerofoils. Because of its slow-landing speed and its great high speed and its burble point occurring at 15°, U. S. A. 1 would make the most satisfactory pursuit machine wing of all U. S. A. aerofoil with the greatest speed range of any U. S. A. aerofoils. Structurally it is excellent.

U. S. A. 4, with its large K_y of 0.00364, would be suitable and very desirable for heavy machines and for machines in which the designer is attempting to obtain a very slow landing speed. It is unsuitable for high speeds because of its low $\frac{L}{D}$ values at small values of K_y. Structurally it is excellent.

U. S. A. 6 has a maximum $\frac{L}{D}$ of 17.4, being second in this particular only to U. S. A. 1, of which the maximum $\frac{L}{D}$ is 17.8. On both U. S. A. 6 and U. S. A. 1 the maximum $\frac{L}{D}$ occurs at 3°. In each the maximum K_y is only fair. The maximum K_y of U. S. A. 1 is better than that of U. S. A. 6, so pursuit machines using U. S. A. 1 could be designed to have a slower landing speed than those using U. S. A. 6. It would appear, judging from the tabulation U. S. A. aerofoils just given, that U. S. A. 6 has better $\frac{L}{D}$ values than has U. S. A. 1 for small values of K_y. However, when we examine this characteristic for many points, it is found that U. S. A. 1 has usually better $\frac{L}{D}$ values for small values of K_y than has U. S. A. 6. Thus it seems that U. S. A. 1 is better than U. S. A. 6 for a pursuit machine. However, U. S. A. 6 could be used on a high-speed machine that is only a trifle slower than the machines using U. S. A. 1, but the machine using U. S. A. 6 would land much faster than the one using U. S. A. 1. At 3°, the angle of maximum $\frac{L}{D}$ for both U. S. A. 1 and U. S. A. 6, the center of pressure movement of U. S. A. 6 is better than that of U. S. A. 1. U. S. A. 6 is undesirable for use on a heavy airplane. Structurally it is satisfactory.

U. S. A. 2 is next best to U. S. A. 4 for heavy machines or machines designed for slow speeds. It is unsatisfactory for a pursuit airplane. Structurally it is satisfactory.

U. S. A. 3 and U. S. A. 5 are above the average of aerofoils.

An off-hand estimate of the U. S. A. aerofoils would arrange them in order of merit as follows, but actual calculation might change this order.

U. S. A. aerofoils arranged in order of preference.	For carrying heavy loads or for slow landing speeds.	For pursuit airplanes.
Best	U. S. A. 4	U. S. A. 1.
Second best	U. S. A. 2	U. S. A. 6.
Third best	U. S. A. 5	U. S. A. 5.
Fourth best	U. S. A. 3	U. S. A. 3.
Fifth best	U. S. A. 1	U. S. A. 2.
Sixth best (worst)	U. S. A. 6	U. S. A. 4.

The general rules we have do not permit us to choose between two aerofoils of nearly the same characteristics, so a designer should actually go through the necessary computations, using each of the several possible aerofoils in order to ascertain which aerofoil is the best for the purposes of his design. As a matter of interest rough calculations are here given for a pursuit machine, and designers can follow the general method used herein for any type of airplane they may happen to be designing.

Among the U. S. A. aerofoils, it seems apparent that U. S. A. 1 or U. S. A. 6 is best for a pursuit machine. For reasonable comparisons, the weight, horsepower available, and the parasite resistance should be the same for both machines. The weight will be assumed as 1,200 pounds, the parasite resistance as being represented by 0.025 V^2 in pounds per square foot per mile per hour units, and the propeller efficiency as given by the following table, though such a propeller might be difficult to obtain in practice:

V in *mph*	50	60	70	80	90	100	110	120
Efficiency	50	55	60	65	70	75	70	60

The horsepower available curve and the parasite resistance curve can then be plotted, the brake horsepower of the motor being assumed as 150. We may either assume a constant wing area and ascertain which wing section gives the best performances or we may prescribe certain performances and see which aerofoil section will come closer to or better the performances. This will result in variations in wing area and minor changes in weight which can be neglected. A low speed will be taken as 55 miles per hour. This will determine the area. The high speed and climb are to be the best obtainable under the assumed conditions.

Using the equation $W = Ky\, A V^2$ we have $1200 = -Ky\, A \frac{2}{55}$. The highest Ky of U. S. A. 1 is .00318 and of U. S. A. 6 is .00298, giving as areas required if U. S. A. 1 is used 124.5 square feet; if U. S. A. 6 is used 133.5 square feet.

$$1200 = (Ky)\ (124.5)\ (V^2) \text{ or}$$

$$Ky = \frac{1200}{(124.5)\ (V^2)}$$

U. S. A. 1 where $A = 124.5$ square feet.			U. S. A. 6 where $A = 133.5$ square feet.		
V	Ky	Angle of incidence.	V	Ky	Angle of incidence.
		°			°
55	0.00318	15.0	55	0.00297	14.0
60	.002675	10.6	60	.00249	8.6
70	.001965	6.5	70	.001833	5.0
80	.001503	4.0	80	.001404	2.8
90	.001188	2.3	90	.001109	1.3
100	.000964	1.2	100	.00089	0.2
110	.000796	0.4	110	.000742	−0.4
120	.000670	−0.2	120	.000624	−0.8

Parasite resistance $= 0.025\ V^2$.	
V miles per hour.	Parasite resistance in pounds.
55	75.6
60	90.0
70	122.5
80	160.0
90	202.0
100	250.0
110	302.0
120	360.0

Drag.

U. S. A. 1.			U. S. A. 6.		
V miles per hour.	*K x.*	Pounds drag.	*V* miles per hour.	*K x.*	Pounds drag.
55	0.00033	124.5	55	0.000405	163.5
60	.00033	93.6	60	.00018	86.6
70	.000125	76.4	70	.000115	75
80	.000085	87.7	80	.00008	68.4
90	.000070	70.6	90	.00007	75.6
100	.000065	81	100	.000064	85.4
110	.000065	98	110	.000065	106
120	.000065	116.5	120	.000067	129

U. S. A. 1.				U. S. A. 6.			
V miles per hour.	Parasite *R*.	Wing *R*.	Total *R* in pounds.	*V* miles per hour.	Parasite *R*.	Wing *R*.	Total *R* in pounds.
55	75.6	134.5	200.1	55	75.6	163.5	239.1
60	90	93.6	183.6	60	90	86.6	176.6
70	122.5	78.4	198.9	70	122.6	75	197.5
80	160	67.7	227.7	80	160	66.4	228.4
90	203	70.6	272.6	90	302	75.5	377.6
100	250	81	331	100	250	85.4	355.4
110	303	98	400	110	303	106	408
120	360	116.5	476.5	120	360	129	469

Horsepower required.			
U. S. A. 1.		U. S. A. 6.	
V miles per hour.	Horsepower required.	*V* miles per hour.	Horsepower required.
55	29.3	55	35.0
60	30.7	60	28.6
70	37.2	70	36.8
80	48.5	80	48.7
90	65.3	90	66.4
100	88.0	100	89.3
110	117.0	110	119.5
120	152.0	120	156.0

V miles per hour.	Propeller efficiency.	Horsepower—boiler horsepower × efficiency.	Horsepower for climb U. S. A. 1.	Climb per minute U. S. A. 1.	Horsepower for climb U. S. A. 6.	Climb per minute U. S. A. 6.
				Feet.		*Feet.*
55	52.5	78.8	49.5	1,360	43.8	1,205
60	55.0	82.4	51.7	1,420	53.8	1,480
70	60.0	90.0	52.8	1,450	53.2	1,460
80	65.0	97.5	49.0	1,345	48.8	1,340
90	70.0	105.0	39.7	1,090	38.6	1,062
100	75.0	112.5	24.5	673	23.2	638
110	70.0	105.0	----------	----------	----------	----------
120	60.0	90.0	----------	----------	----------	----------

Thus we see that actual calculations demonstrate that U. S. A. 1 is better than U. S. A. 6 for a pursuit machine, considering speed above, for it has a greater high speed.

The best climb of U. S. A. 1 is 1,450 feet per minute at 70 miles per hour and for U. S. A. 6 it is 1,480 feet per minute at 60 miles per hour. Although U. S. A. 6 can climb 30 feet per minute faster than U. S. A. 1, yet the speed of U. S. A. 6 at which best climb occurs is 10 miles per hour less than the speed for the best climb of U. S. A 1. We believe that the climbing ability of U. S. A. 1 is better for a pursuit machine than is that of U. S. A. 6. Hence U. S. A. 1 excels U. S. A. 6 in both speed and climb characteristics.

The above process should be pursued whenever there is any doubt between the relative desirability of two or more wing sections for specific purposes.

It would seem that Dr. Hunsaker is a trifle low in his estimate wherein he states that an increase in camber above 0.08 for the upper surface is disadvantageous, since four good U. S. A. aerofoils are cambered as follows:

U. S. A. 2 has a camber of 0.088 per cent of the chord.
U. S. A. 3 has a camber of 0.0868 per cent of the chord.
U. S. A. 4 has a camber of 0.089 per cent of the chord.
U. S. A. 5 has a camber of 0.085 per cent of the chord.

It is generally conceded that the angle of no lift has no connection with the characteristics of an aerofoil. As a matter of interest the angle of no lift occurs in the U. S. A. aerofoil as follows:

Aerofoil.	Angle of no lift.
	°
U. S. A. 1	−2.5
U. S. A. 2	−3.25
U. S. A. 3	−2.9
U. S. A. 4	−3.6
U. S. A. 5	−3.05
U. S. A. 6	−2.9

Aerofoils arranged in order of maximum negative angle of no lift.	Aerofoils arranged in order of preference as weight carriers or slow-speed qualities.
U. S. A. 4	U. S. A. 4.
U. S. A. 2	U. S. A. 2.
U. S. A. 5	U. S. A. 5.
U. S. A. 3 and U. S. A. 6	U. S. A. 3.
U. S. A. 1	U. S. A. 1.
	U. S. A. 6.

From the above table it appears that perhaps at some future date it might be desirable to investigate whether or not the aerofoil with the greatest negative angle of no lift is also the best aerofoil for heavy aeroplanes or aeroplanes designed for slow speeds.

Since the lowest value of K_x in the U. S. A. aerofoils occurs in U. S. A. 6, a designer designing for high speed only with no thought of other considerations, could probably obtain a higher speed with U. S. A. 6 than with any of the other U. S. A. aerofoils.

In order to check the valves that we have obtained in the tests of the U. S. A. aerofoils, as R. A. F. 6 section made of wood was tested and found to conform to former tests which are known to be satisfactory.

An examination of all the published $\frac{L}{D}$ curves of the R. A. F. sections tested at the M. I. T. tunnel show the maximum $\frac{L}{D}$ obtained varied between a little less than 16 to a trifle above 17. Our maximum $\frac{L}{D}$ is equal to 16.78. On page 41 of "Reports on Wind Tunnel Experiments in Aerodynamics," Dr. Hunsaker says "It appears that undetected differences in workmanship and finish between two models may cause a change in coefficients of not more than 3 per cent." Let us assume for all R. A. F. sections tested at the M. I. T. tunnel L and D are correct within 3 per cent.

$$\text{Possible error in } \frac{L}{D} - \frac{L+.03L}{D-.03D}$$

$$= \frac{L(1.03)}{D(.97)} = \frac{L}{D}(1.06)$$

or if the error be at the other extreme

$$\text{Possible error in } \frac{L}{D} = \frac{L-.03L}{D+.03D} = \frac{.97L}{1.03D}$$

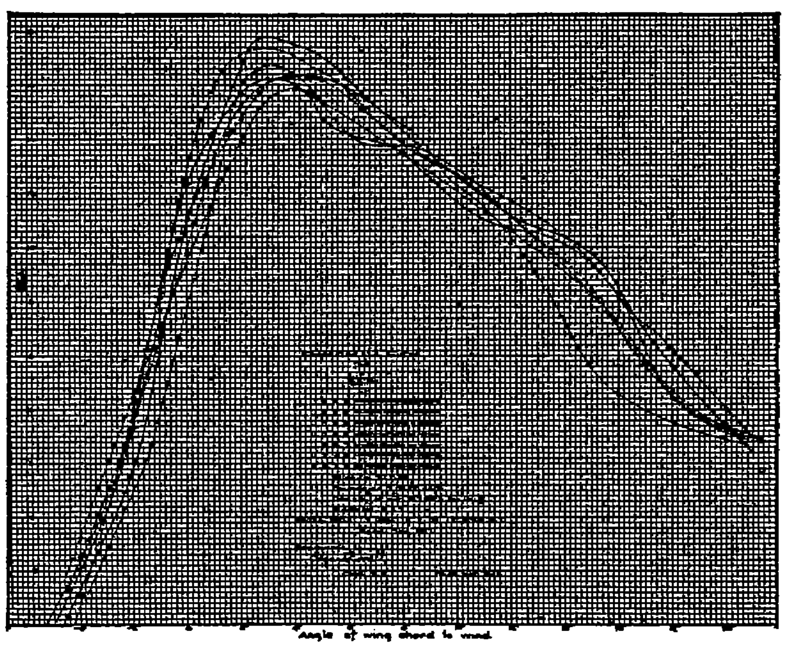
$$= \frac{L}{D}(0.94)$$

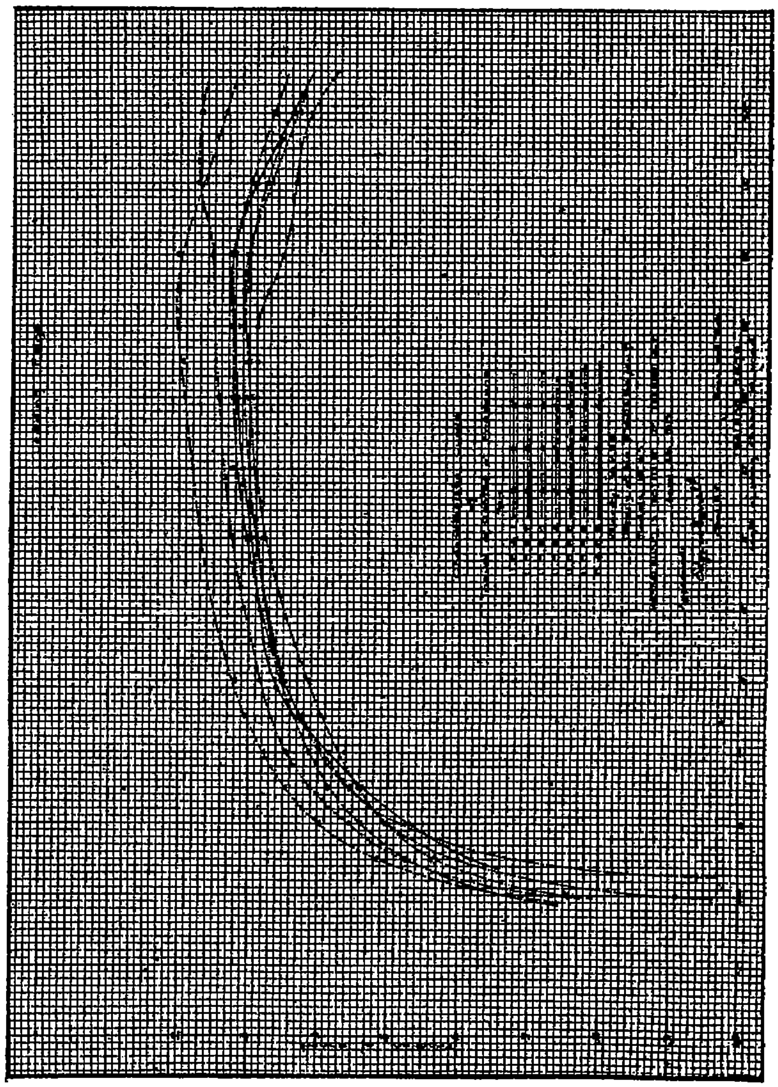
It is thus seen that all published results of the M. I. T. on tests of R. A. F. 6 are correct within the limits of workmanship and finish and that our test gives a result about the mean of all such tests.

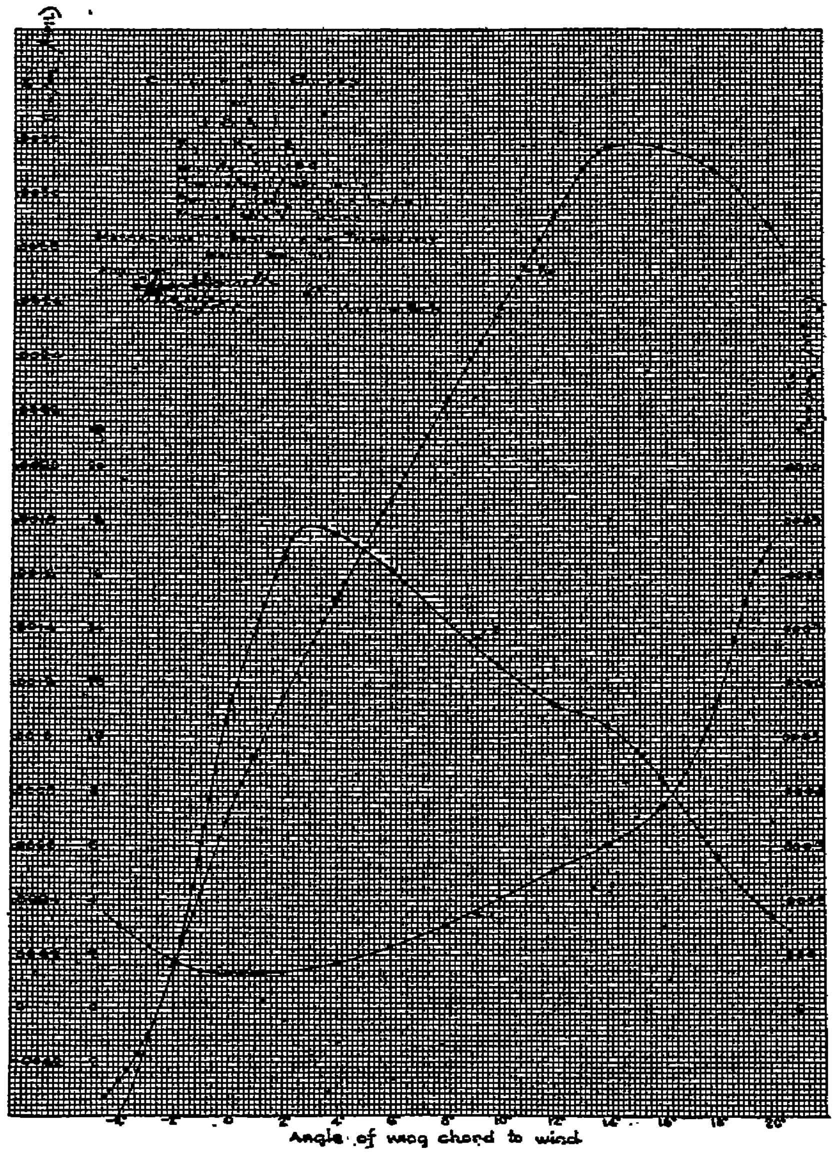
It is suggested that it might be well if the United States Government owned standard brass aerofoils of the R. A. F. and Eiffel types constructed with absolute accuracy and which could be available for use on wind tunnels like the one at the M. I. T. for checking the accuracy of the tunnel whenever desirable. The Government has standard weights and measurements. Why not apply this same idea to aeronautics?

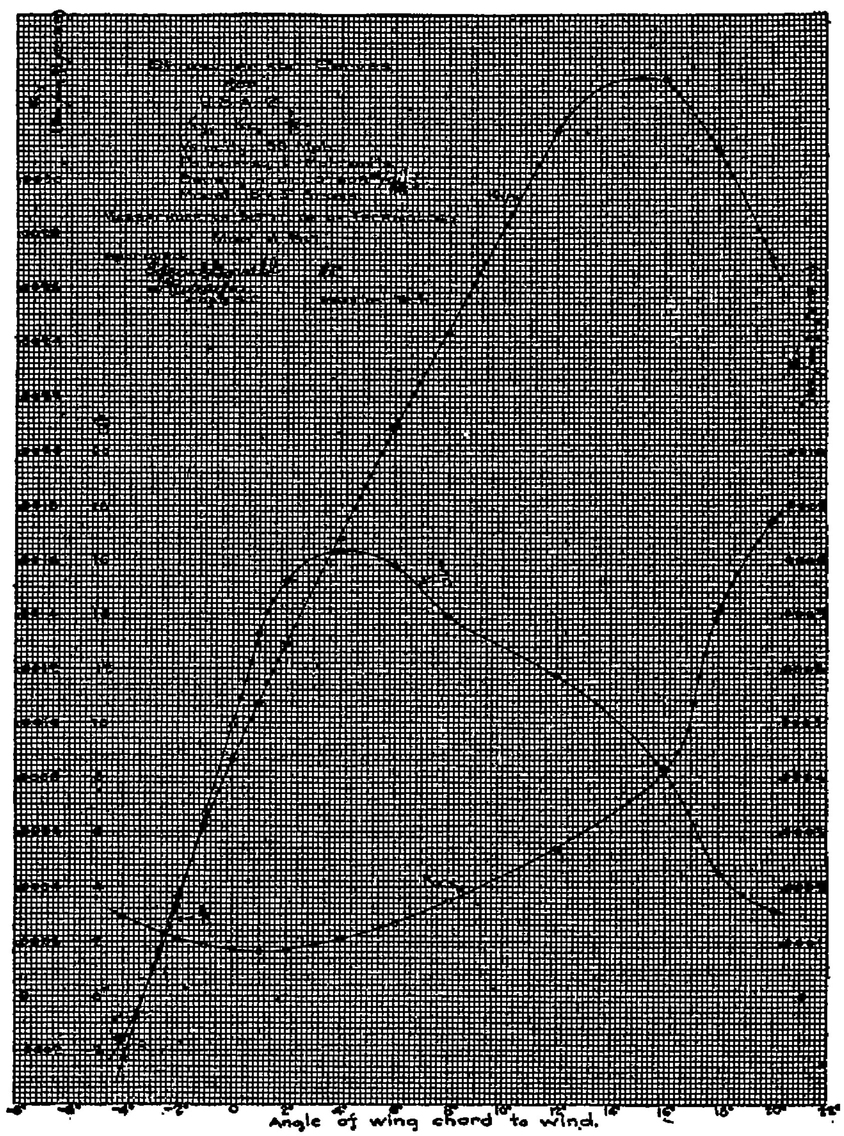
In British Reports, 1912–13, No. 72, figure 14, the National Advisory Committee for aeronautics in England has suggested a method of corrections for LV. U. S. A. aerofoils were tested at an LV of 11 while R. A. F. 3, 4, 5, and 6 were tested at an LV of 6.3. Making the proper LV correction for the English tests of the R. A. F. 6, we find the N. P. L. results and our results for tests on the R. A. F. 6 give the same maximum $\frac{L}{D}$, thus checking the accuracy of our series of tests. Reducing the R. A. F. and the U. S. A. aerofoils to the same LV and tabulating the results we obtain the following:

Aerofoils arranged in order of merit for maximum $\frac{L}{D}$.	Maximum $\frac{L}{D}$ reduced to same LV.
U. S. A. 1	17.6
U. S. A. 6	17.4
R. A. F. 6	16.78
R. A. F. 3	16.44
U. S. A. 3	16.4
U. S. A. 2	16.3
U. S. A. 5	16.21
U. S. A. 4	15.86
R. A. F. 4	15.86
R. A. F. 5	15.8

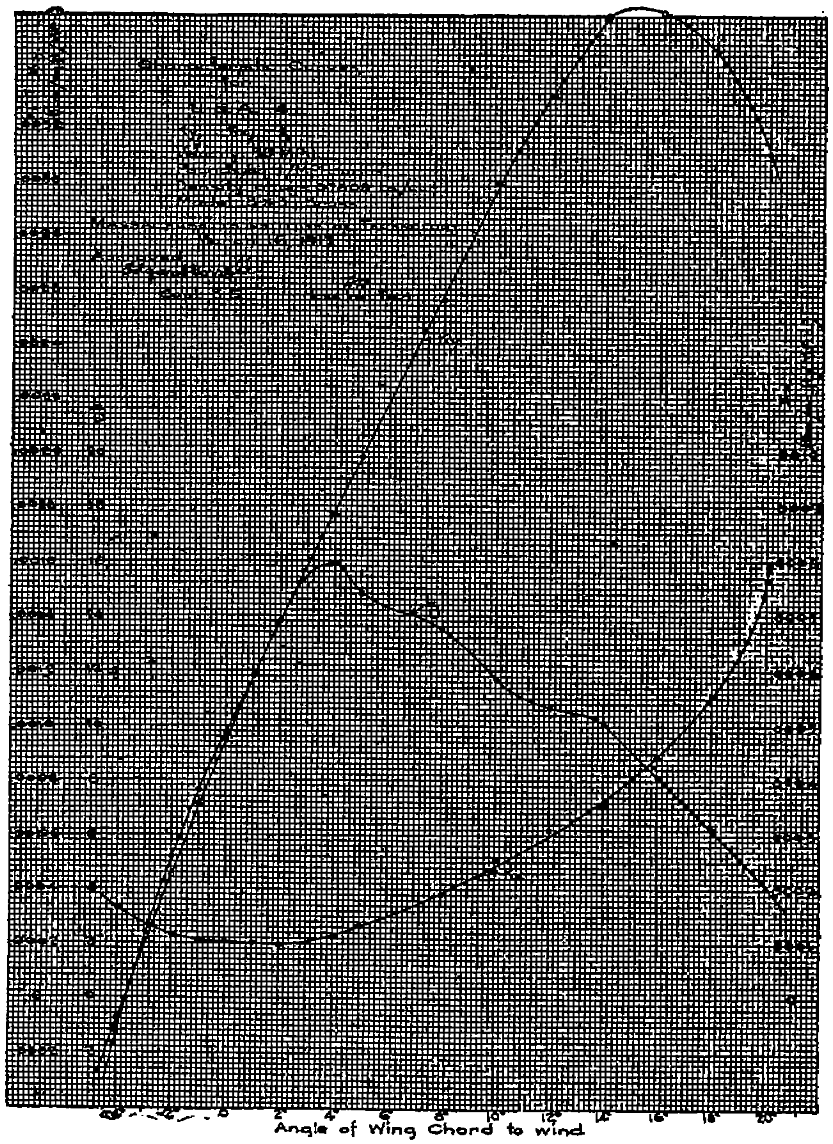




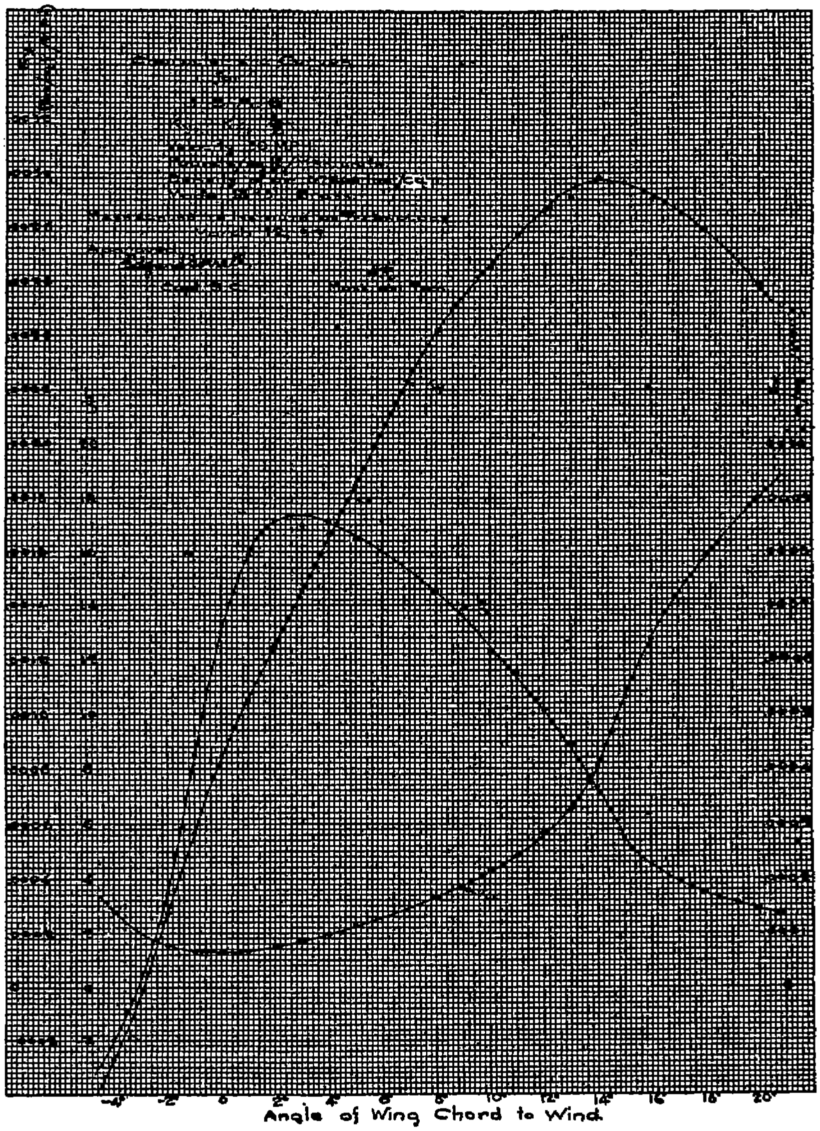

Angle of wing chord to wind

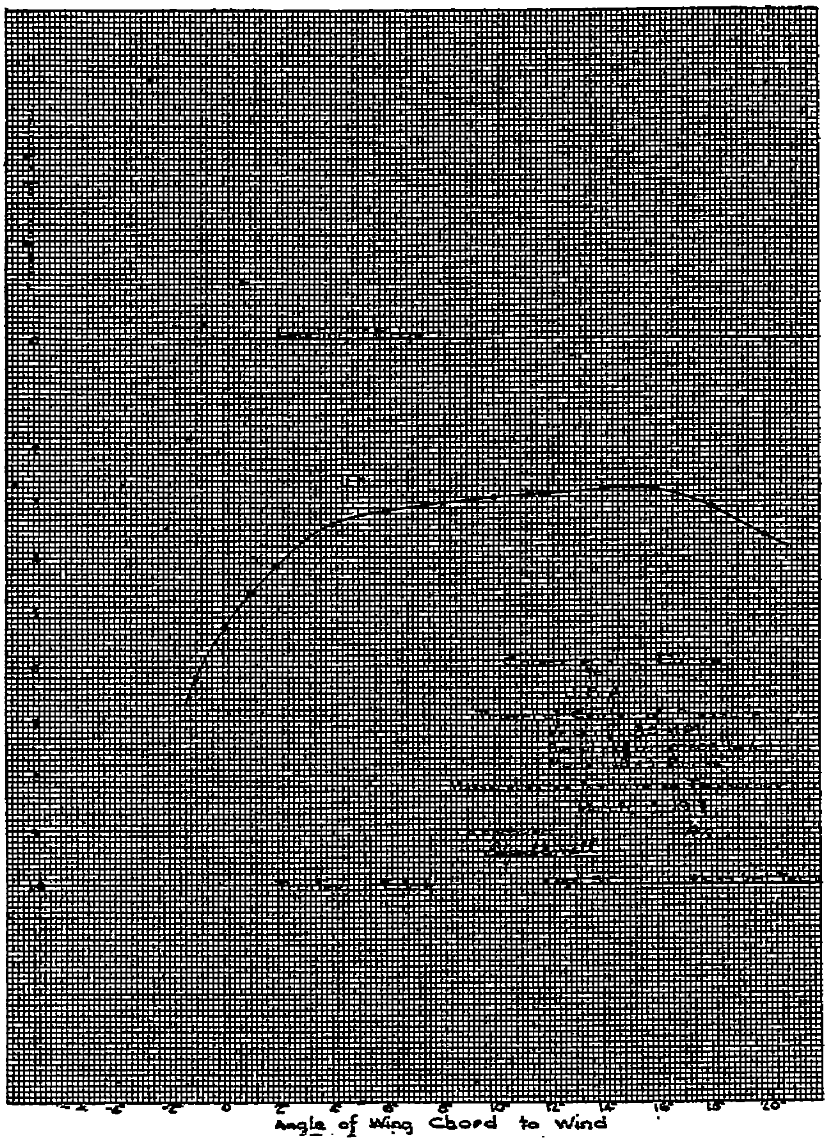

Angle of wing chord to wind.

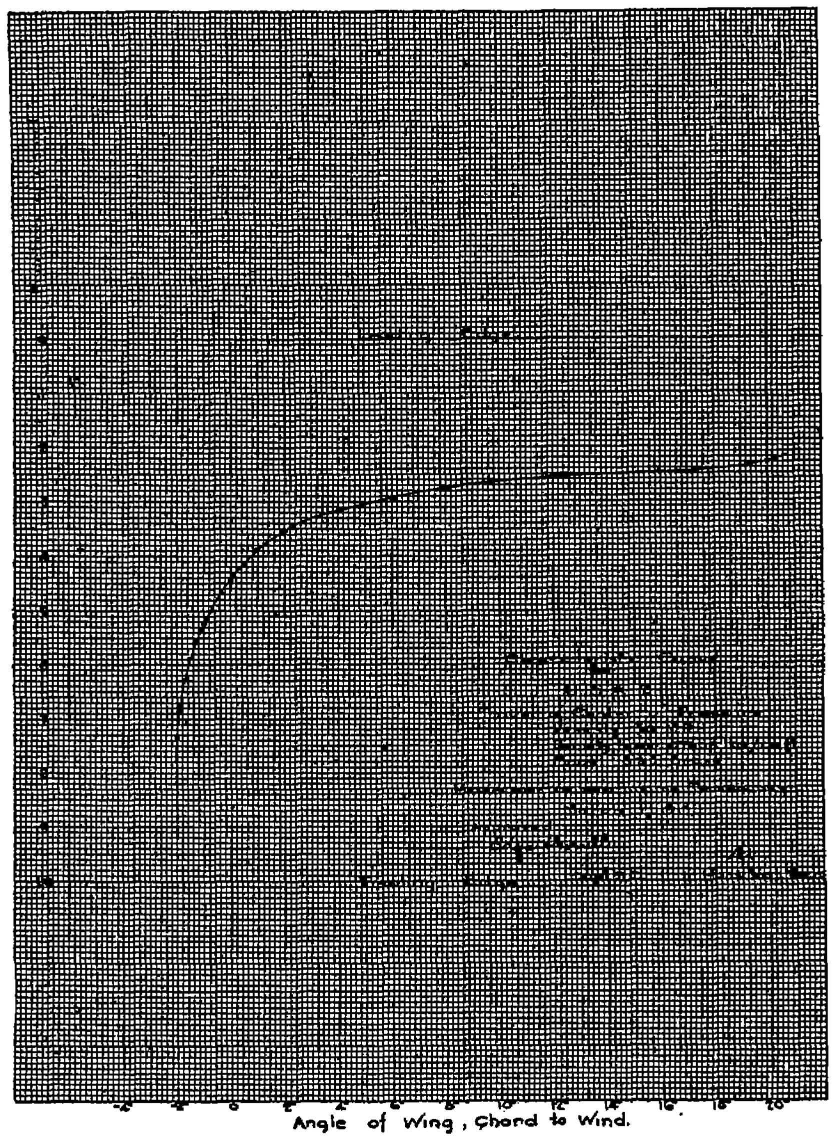

Angle of wing chord to wind.

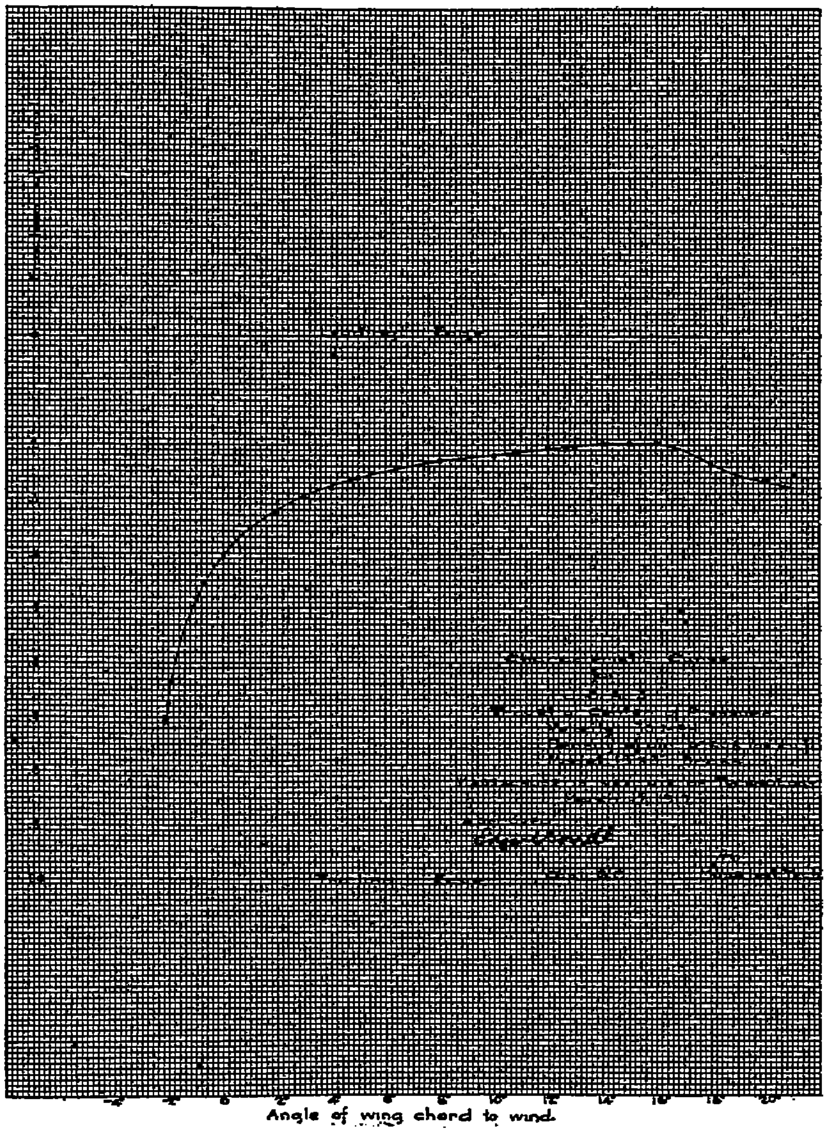

Angle of Wing Chord to wind

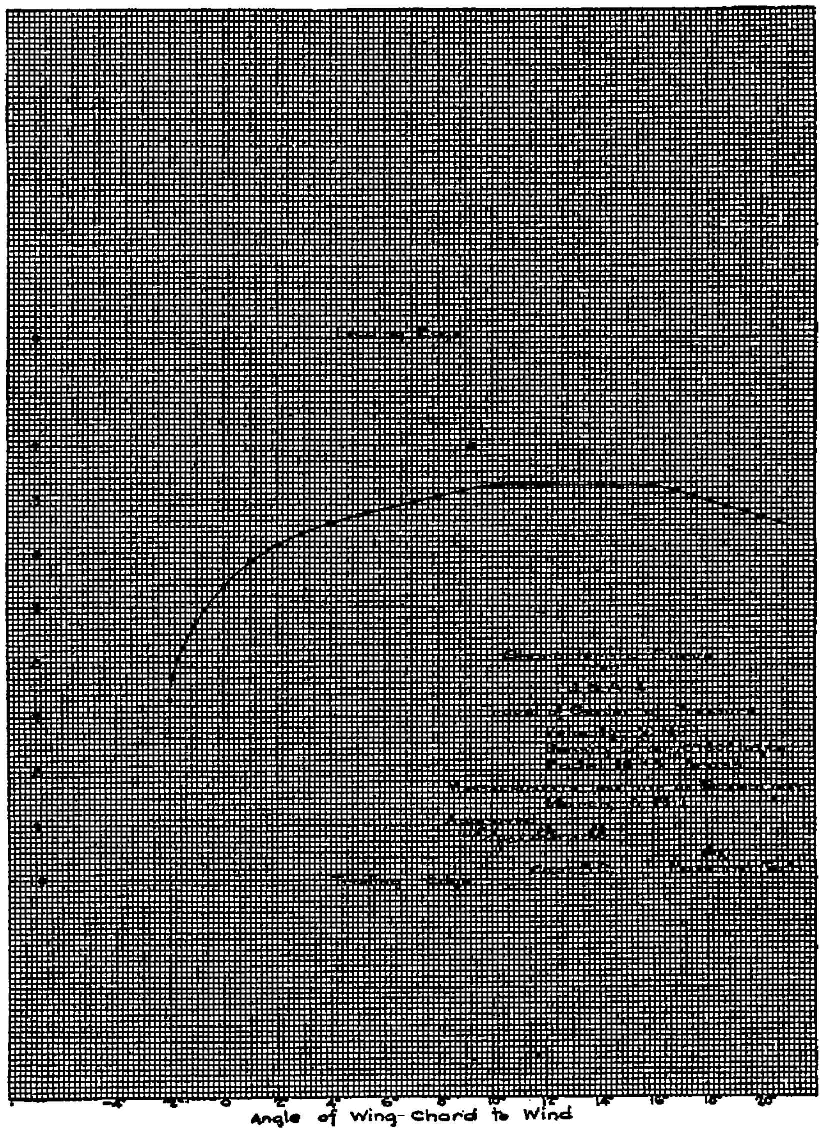

-4°
-2°
0
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
Angle of wing chord to wind.

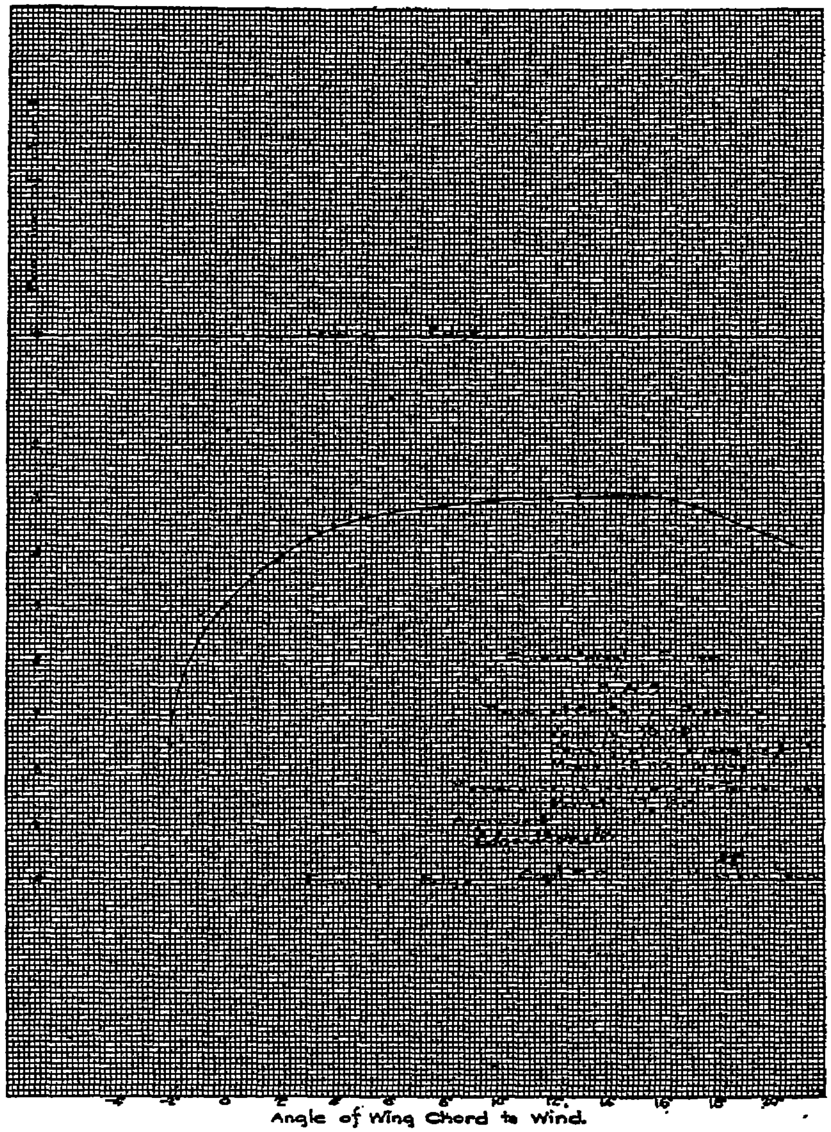

-4° -2° 0 2° 4° 6° 8° 10° 12° 14° 16° 18° 20°
Angle of Wing Chord to Wind

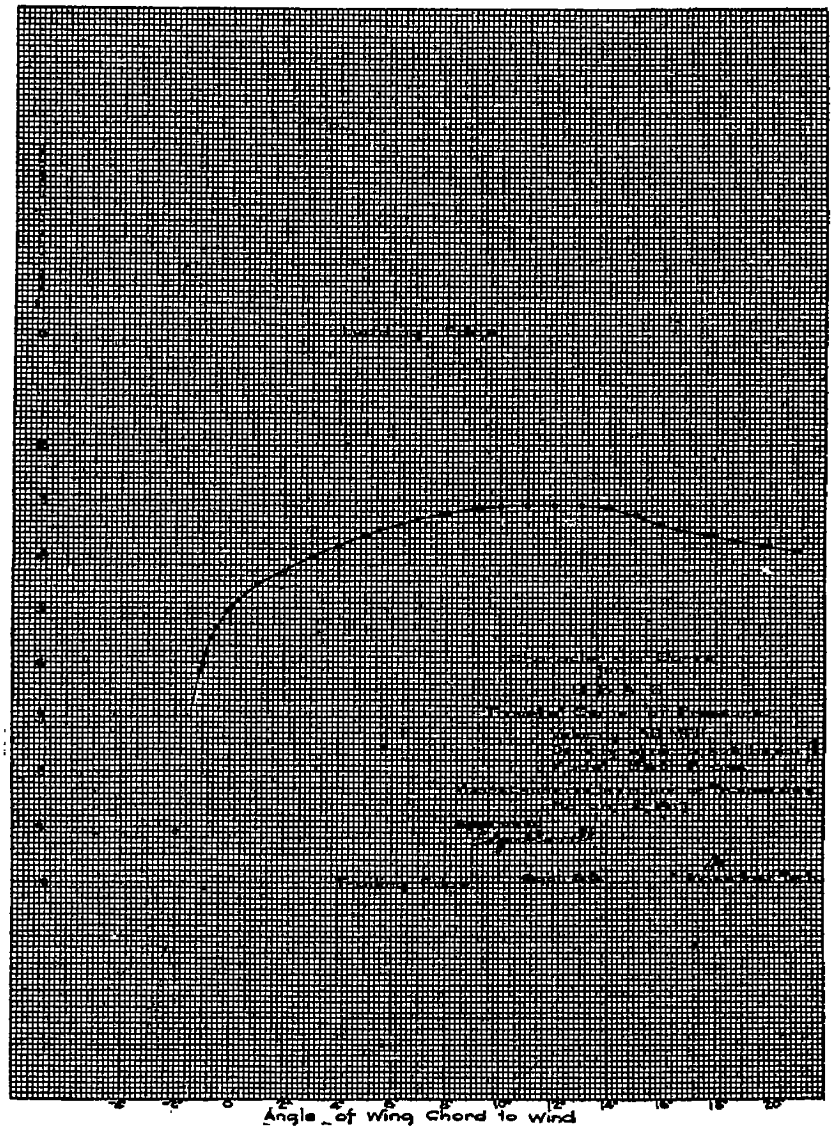

Angle of Wing Chord to Wind

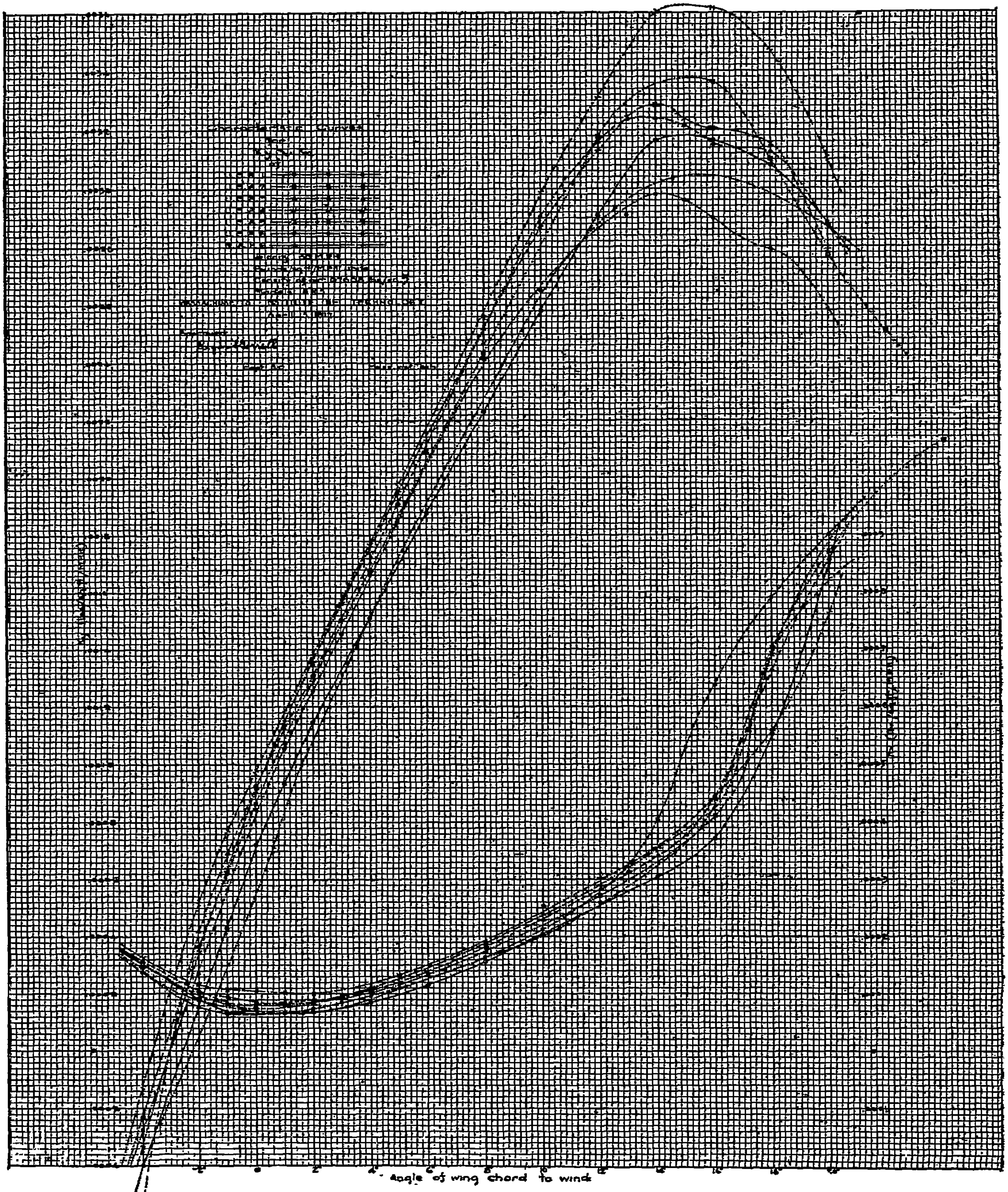

Angle of Wing, Chord to Wind.


Angle of wing chord to wind.


-4°
-2°
0
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
Angle of Wing-Chord to Wind




Angle of Wing Chord to Wind

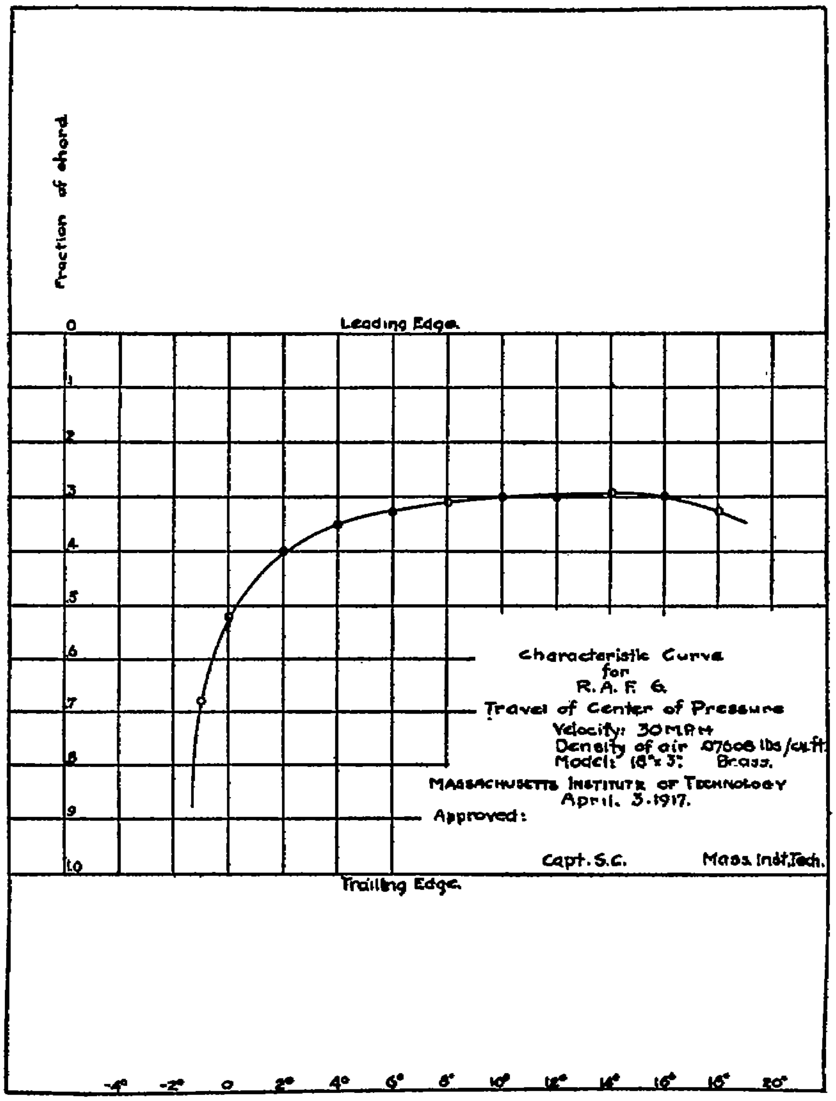


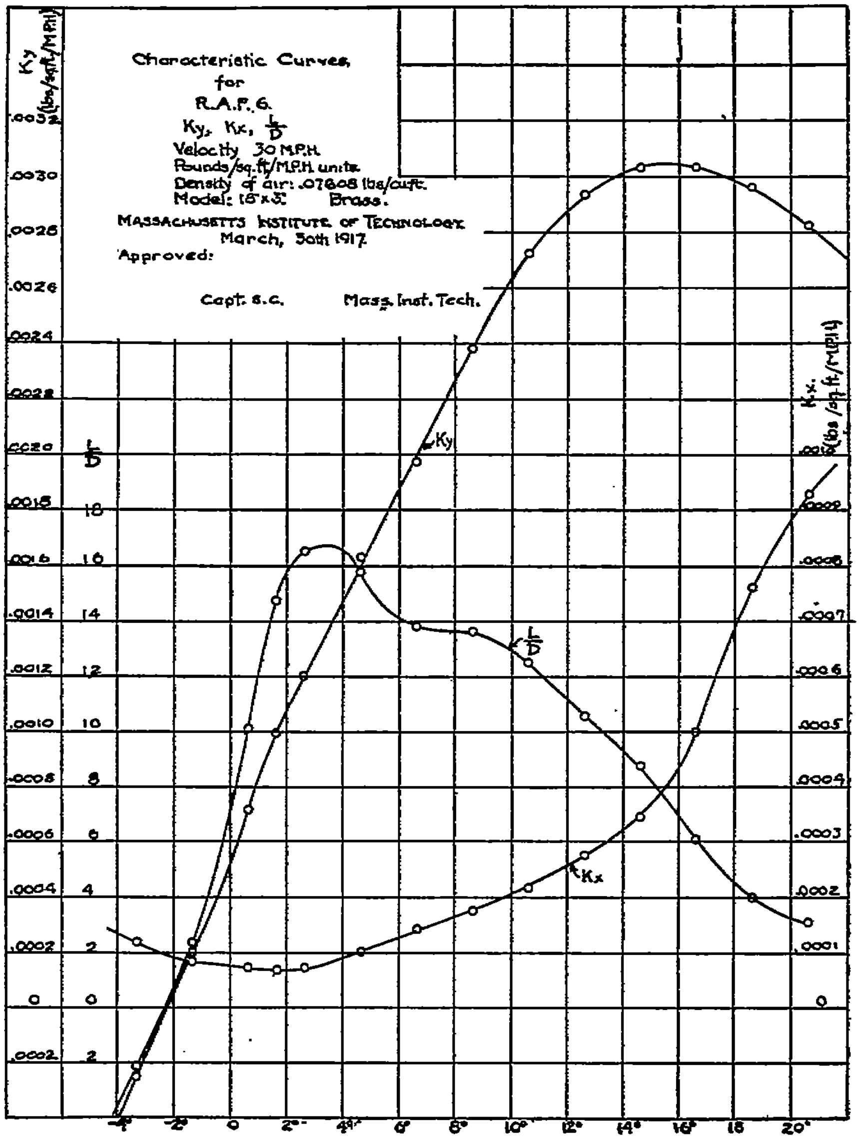
29165°—S. Doc. 123, 65-2. (To face page 370.)

U. S. AEROFOILS

AVIATION SECTION U. S. A. SIGNAL CORPS

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		ORDINATES	.0	.0125	.025	.05	.075	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
USA 1	UPPER	% CHORD	[illegible]	.0250	.0344	.0471	.0558	.061	[illegible]	.0761	.0755	.0711	.0636	[illegible]	.0390	.0247	[illegible]
		30" CHORD	[illegible]	.750	[illegible]	1.415	1.675	[illegible]	2.184	[illegible]	[illegible]	2.133	1.908	1.596	1.170	.741	[illegible]
	LOWER	%	[illegible]	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	.0003	.0047
		30"	.243	[illegible]	.057	0	[illegible]	.117	.480	.681	.664	.516	.313	.198	0	.009	.141
USA 2	UPPER	%	.008	.018	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.088	.085	[illegible]	[illegible]	[illegible]	.0412	.0248	.007
		30"	.240	.546	.895	1.315	1.646	1.815	2.52	2.64	2.55	2.355	[illegible]	1.685	1.235	.745	.210
	LOWER	%	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
		30"	0	.081	.149	.267	.369	.475	.67	.772	.816	.76	.585	.38	.215	.09	0
USA 3	UPPER	%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0775	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		30"	[illegible]	.56	.792	1.173	1.51	1.794	2.48	2.644	2.572	2.329	2.044	1.671	1.224	.717	.207
	LOWER	%	0	.0013	.003	.0062	.009	.0115	[illegible]	.023	.025	[illegible]	.0178	.0115	[illegible]	[illegible]	0
		30"	0	.04	.09	.186	.27	.345	.56	.69	.75	.70	.535	.345	.19	.10	0
USA 4	UPPER	%	.0081	.0243	.0344	.0488	.060	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0071
		30"	.243	.73	1.032	1.464	1.80	2.049	2.571	[illegible]	2.871	[illegible]	2.07	1.68	1.224	.696	.213
	LOWER	%	0	.0025	[illegible]	.0107	.0147	.0182	.0257	.0283	.0293	[illegible]	.0198	.0122	[illegible]	.003	0
		30"	0	.075	.144	.32	.44	.545	.77	.85	.88	.79	.596	.365	.186	.09	0
USA 5	UPPER	%	.0073	.021	[illegible]	[illegible]	.054	[illegible]	[illegible]	[illegible]	.0814	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.005
		30"	.219	.63	.91	1.32	1.62	1.86	[illegible]	2.43	[illegible]	[illegible]	[illegible]	1.69	[illegible]	.783	.15
	LOWER	%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0116	[illegible]	[illegible]	0
		30"	.099	.05	.01	.01	.075	.17	.465	[illegible]	[illegible]	[illegible]	.463	.348	.225	.105	0
USA 6	UPPER	%	[illegible]	.0177	[illegible]	[illegible]	[illegible]	[illegible]	.069	.074	[illegible]	[illegible]	[illegible]	.0491	[illegible]	.0201	[illegible]
		30"	.2166	.53	[illegible]	1.041	1.325	1.599	2.07	2.22	2.246	[illegible]	1.809	1.476	[illegible]	[illegible]	.087
	LOWER	%	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		30"	.2160	.075	0	[illegible]	[illegible]	.189	[illegible]	[illegible]	.87	.756	.579	.396	.216	[illegible]	[illegible]
USA 7	UPPER	%	.0125	[illegible]	[illegible]	[illegible]	.1130	.1328	[illegible]	[illegible]	[illegible]	[illegible]	.1723	.1437	.1060	[illegible]	[illegible]
		30"	.375	1.02	1.615	2.61	3.39	3.985	5.38	6.03	6.15	[illegible]	5.17	4.31	3.18	1.875	.45
	LOWER	%	0	.0107	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
		30"	0	[illegible]	[illegible]	[illegible]	.64	.94	1.14	[illegible]	1.16	1.095	.91	.75	[illegible]	[illegible]	0
USA 8	UPPER	%	[illegible]	.0465	.0633	.0873	.1021	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.1163	.0974	[illegible]	.045	[illegible]
		30"	.375	1.395	1.90	2.619	3.063	3.375	[illegible]	4.179	[illegible]	[illegible]	3.489	[illegible]	2.185	1.35	.42
	LOWER	%	0	.0038	.0058	.0081	.0095	[illegible]	[illegible]	.0129	.0128	[illegible]	.0109	.0091	[illegible]	.0040	0
		30	0	.115	.174	.243	.285	.315	.366	.387	.384	.36	.327	.273	.198	.120	0
USA 9	UPPER	%	[illegible]	[illegible]	.0458	[illegible]	.0747	.0822	[illegible]	.1007	.100	[illegible]	.0843	.0712	.0556	.0362	.015
		30"	.375	.97	1.374	1.905	2.24	2.465	2.91	3.02	3.00	2.841	2.53	2.136	1.668	1.085	.45
	LOWER	%	0							0							0
		30"	0							0							0
USA 10	UPPER	%	[illegible]	.0243	.0343	.0450	[illegible]	.0632	.0727	.0750	.0745	.0710	.0643	.0538	[illegible]	[illegible]	.0150
		30"	.375	.73	1.03	1.35	1.72	1.895	2.18	2.25	2.235	2.13	1.93	1.615	1.260	.875	.450
	LOWER	%	0							0							0
		30"	0							0							0
USA 11	UPPER	%	[illegible]	.0232	.0321	.0445	.0530	.0585	.0678	[illegible]	.0705	.0663	.0595	[illegible]	[illegible]	[illegible]	.015
		30"	.375	.696	.963	1.335	1.59	1.755	2.035	2.135	2.115	1.989	1.785	1.500	1.175	.83	.45
	LOWER	%	0							0							0
		30"	0							0							0
USA 12	UPPER	%	[illegible]	.0473	.0688	.0954	.114	.1227	.1456	[illegible]	.1507	.142	.1271	.1063	[illegible]	.0497	.015
		30"	.375	1.42	2.064	[illegible]	[illegible]	3.68	4.368	[illegible]	4.52	4.26	3.812	3.19	2.41	1.49	.45
	LOWER	%	0							0							0
		30"	0							0							0


Fraction of chord
Leading Edge.
Trailing Edge.
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
-4°
-2°
0
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
Characteristic Curve
for
R. A. F. 6.
Travel of Center of Pressure
Velocity: 30 M.P.H.
Density of air .07608 lbs/cu.ft.
Model: 18" x 3". Brass.
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
April. 3. 1917.
Approved:
Capt. S.C.
Mass. Inst. Tech.


Characteristic Curves,
for
R.A.F. 6.
Ky, Kx, L/D
Velocity 30 M.P.H.
Pounds/sq.ft/M.P.H. units
Density of air: .07608 lbs/cu.ft.
Model: 18"x3" Brass.
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
March, 30th 1917.
Approved:
Capt. S.C.
Mass. Inst. Tech.
Ky (lbs/sq.ft./M.P.H.)
Kx (lbs/sq.ft./M.P.H.)
L/D
Ky
Kx
L/D

Aerodynamic Laboratory Test.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 1.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
−4	−0.000399	0.0001515	2.64	....
−2	.000156	.0000905	1.72	....
−1	.000432	.0000700	6.15	0.620
0	.000721	.0000653	11.00	.530
1	.000936	.0000670	14.00	.463
2	.001146	.0000688	16.60	.415
4	.001510	.0000860	17.50	.340
6	.001878	.0001158	16.20	.316
8	.002230	.0001558	14.30	.303
10	.002580	.0002055	12.60	.290
12	.002910	.0002595	11.20	.283
14	.003165	.0003040	10.40	.274
16	.003165	.0003710	8.50	.276
18	.003080	.0005520	5.60	.310
20	.002882	.0008500	3.40	.360

L of i = Angle of wing chord to wind.
Ky = Lift coefficient in lbs./sq. ft./MPH.
Kx = Drift coefficient in lbs./sq. ft./MPH.
L/D = Ratio of lift to drift.
Model: Size, 18 by 3 inches (54 sq. in.); material, brass.
Velocity of wind: 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.

Aerodynamic Laboratory Test.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 2.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
−4	−0.000228	0.000147	−1.55	....
−2	.000363	.000108	3.37	0.733
−1	.000625	.0000943	6.64	.522
0	.000862	.0000872	9.88	.445
1	.001075	.0000816	13.26	.388
2	.001292	.0000848	15.22	.352
4	.001678	.0001027	16.34	.317
6	.002090	.0001320	15.80	.292
8	.002432	.000175	13.88	.276
12	.003179	.000270	11.75	.255
16	.003362	.000410	8.20	.247
18	.003100	.000701	4.41	.228
20	.002770	.000871	3.18	.230

L of i—Angle of wing chord to wind.
Ky—Lift coefficient in lbs./sq. ft./MPH.
Kx—Drift coefficient in lbs/sq. ft./MPH.
L/D—Ratio of lift to drift.
Model: Size, 18 by 3 inches (54 sq. in.); material, brass.
Velocity of wind: 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.

Aerodynamic Laboratory Test.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 3.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
−4	−0.000506	0.0001589	−3.19	....
−2	.000420	.0001052	3.99	0.676
−1	.000692	.0000845	8.20	.482
0	.000928	.0000835	11.10	.403
1	.001123	.0000856	13.10	.353
2	.001310	.0000889	14.75	.323
3	.001508	.0000893	16.16	.295
4	.001704	.0001073	15.88	.280
5	.001910	.0001180	16.18	.260
8	.002520	.0001823	13.82	.230
10	.002905	.0002290	12.70	.220
12	.003160	.0002830	11.15	.208
13	.003235	.0003142	10.30	.204
14	.003240	.0003410	9.50	.197
15	.003215	.0003780	8.50	.197
16	.003155	.0004460	7.02	.197
18	.003125	.0006620	4.73	.236
20	.002889	.0008570	3.37	.266

L of i— Angle of wing chrod to wind.
Ky— Lift coefficient in lbs./sq. ft./MPH.
Kx— Drift coefficient in lbs./sq. ft./MPH.
L/D— Ratio of lift to drift.
Velocity of wind: 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.
Model: Size, 18 by 3 inches (54 sq. in.); material, brass.

Aerodynamic Laboratory Test.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 4.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
− 4	−0.0001231	0.0001640	− 0.75	.....
− 2	.0005200	.0001150	4.52	0.670
− 1	.0007650	.0001078	7.11	.525
0	.0009750	.0001032	9.44	.461
1	.0011840	.0001002	11.80	.416
2	.0013820	.0000995	13.90	.388
4	.0017700	.0001115	15.88	.347
5	.0019800	.0001340	14.80	.330
8	.0025600	.0001900	13.50	.298
10	.0029900	.0002555	11.70	.273
12	.0033100	.0003100	10.67	.276
14	.0036000	.0003545	10.15	.276
16	.0036150	.0004430	8.15	.276
18	.0034700	.0005580	6.22	.303
20	.0031000	.0007640	4.06	.335

L of i—Angle of wing chord to wind.
Ky.—Lift coefficient in lbs./sq. ft./MPH.
Kx.—Drift coefficient in lbs./sq. ft./MPH.
L/D.—Ratio of lift to drift.
Velocity of wind, 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.
Model—Size: 18 by 3 inches (54 sq. in.). Material: Brass.

AERODYNAMIC LABORATORY TEST.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 5.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
− 4	−0.000326	0.0001500	− 1.58	.....
− 2	.000346	.0000948	3.64	0.753
− 1	.000636	.0000830	7.67	.566
0	.000910	.0000741	12.28	.498
1	.001145	.0000803	14.28	.444
2	.001355	.0000863	15.72	.415
3	.001565	.0000966	16.21	.377
4	.001740	.0001092	15.98	.348
5	.001950	.0001290	15.35	.337
8	.002470	.0001830	13.52	.315
10	.002870	.0002380	12.08	.303
12	.003130	.0002890	10.84	.300
13	.003240	.0003290	9.84	.298
14	.003285	.0003545	9.25	.288
15	.003235	.0003910	8.28	.292
16	.003205	.0004210	7.63	.298
18	.003150	.0006900	4.57	.330
20	.002790	.0008200	3.41	.368

L of i.—Angle of wing chord to wind.
Ky.—Lift coefficient in lbs./sq. ft./MPH.
Kx.—Drift coefficient in lbs./sq. ft./MPH.
L/D.—Ratio of lift to drift.
Velocity of wind: 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.
Model—Size: 18 by 3 inches (54 sq. in.). Material: Brass.

Aerodynamic Laboratory Test.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

U. S. A. 6.

L of i.	Ky.	Kx.	L/D.	Distance of C. P. from leading edge, in fractional part of chord.
°				
−4	−0.000276	0.0001395	−1.98	.....
−2	.000272	.0000793	3.43	0.910
−1	.000567	.0000671	8.46	.600
0	.000845	.0000650	13.00	.498
1	.001057	.0000668	15.88	.458
2	.001255	.0000733	17.15	.439
3	.001455	.0000858	16.98	.402
4	.001662	.0000976	17.05	.388
5	.001846	.0001121	16.48	.365
8	.002415	.0001665	14.50	.322
10	.002650	.0002160	12.27	.306
12	.002861	.0002820	10.15	.310
13	.002910	.0003260	8.94	.310
14	.002980	.0004050	7.37	.310
15	.002960	.0005300	5.58	.328
16	.002900	.0006380	4.55	.346
18	.002790	.0007900	3.53	.365
20	.002585	.0009000	2.88	.388

L of i.—Angle of wing chord to wind.
Ky.—Lift coefficient to lbs./sq. ft./MPH.
Kx.—Drift coefficient in lbs./sq. ft./MPH.
L/D.—Ratio of lift to drift.
Velocity of wind: 30 MPH.
Density of standard air: 0.07608 lbs./cu. ft.
Model—Size: 18 by 3 inches (54 sq. in.). Material: Brass.